RI9439

C2

RI 9439

REPORT OF INVESTIGATIONS/1992

A Summary of Current Bureau Research Into the Effects of Whole-Body Vibration and Shock on Operators of Underground Mobile Equipment

By Arnold C. Love, Richard L. Unger, Thomas G. Bobick, and Richard S. Fowkes

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

Mission: As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally-owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also promotes the goals of the Take Pride in America campaign by encouraging stewardship and citizen responsibility for the public lands and promoting citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. Administration.

Report of Investigations 9439

A Summary of Current Bureau Research Into the Effects of Whole-Body Vibration and Shock on Operators of Underground Mobile Equipment

By Arnold C. Love, Richard L. Unger, Thomas G. Bobick, and Richard S. Fowkes

UNITED STATES DEPARTMENT OF THE INTERIOR
Manuel Lujan, Jr., Secretary

BUREAU OF MINES
T S Ary, Director

Library of Congress Cataloging in Publication Data:

A Summary of current bureau research into the effects of whole-body vibration and shock on operators of underground mobile equipment / by Arnold C. Love ... [et al.].

p. cm. — (Report of investigations / United States Department of the Interior, Bureau of Mines; 9439)

Includes bibliographical references (p. 14).

Supt. of Docs. no.: I 28.23:9439.

1. Coal mines and mining—Health aspects. 2. Vibration—Physiological effect. 3. Vibration syndrome. I. Love, Arnold C. II. Series: Report of investigations (United States. Bureau of Mines); 9439.

TN23.U43 [RC965.M5] 622 s—dc20 [616.9'896] 92-23710 CIP

CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

dB	decibel
g	gravity
h	hour
hp	horsepower
Hz	hertz
in	inch
kHz	kilohertz
min	minute
mmHg	millimeter of mercury
m/s^2	meter per second squared
$pC/m{\cdot}s^{-2}$	picocoulomb per meter per second squared
pct	percent
s	second
V	volt
V/pC	volt per picocoulomb

A SUMMARY OF CURRENT BUREAU RESEARCH INTO THE EFFECTS OF WHOLE-BODY VIBRATION AND SHOCK ON OPERATORS OF UNDERGROUND MOBILE EQUIPMENT

By Arnold C. Love,[1] Richard L. Unger,[2] Thomas G. Bobick,[3] and Richard S. Fowkes[4]

ABSTRACT

This report discusses current research by the U.S. Bureau of Mines on the effects of whole-body vibration (WBV) and shock on underground mobile equipment operators. The highlights of a comprehensive literature review of WBV, shock, and seating are presented. Factors discussed include health and physiological effects, comfort, performance, and fatigue. Vibration data were collected from shuttle cars and ramcars at several underground coal mines in Pennsylvania, Ohio, and Illinois. The data were formatted so that they could be used to drive the Bureau's motion platform, and to compare them with ANSI S3-1979, Guide for the Evaluation of Human Exposure to Whole-Body Vibration. Human subject testing in the Bureau's vibration research laboratory evaluated the effects of two different seat angles and of the presence or absence of vibration and of foam padding on heart rate, blood pressure, and subjective discomfort. Only vibration significantly increased heart rate and systolic and mean blood pressures. Vibration and a steel seat had a significant effect on subjective discomfort. The apparatus used for these tests and the experimental procedures are described in detail. Recommendations are made for additional research on the exposure of underground mining machine operators to WBV and shock.

[1]Industrial engineer (now with Ford Motor Co., Dearborn, MI).
[2]Civil engineer.
[3]Mining engineer (now with National Institute for Occupational Safety and Health, Morgantown, WV).
[4]Research physicist.
Pittsburgh Research Center, U.S. Bureau of Mines, Pittsburgh, PA.

INTRODUCTION

The key question originally addressed by the U.S. Bureau of Mines was, "Is the amount of whole-body vibration (WBV) to which operators of underground mining equipment are exposed detrimental?" To answer this question, WBV experienced by workers during a full shift was measured, and the results were compared with the acceptable limits for WBV as given by the International Standards Organization (ISO). A second important question was, "If the exposure of some or all of the operators of underground mining equipment does exceed the ISO limits, then what should and what can be done about it?" The present project came about because these limits were exceeded for a significant number of operators. Some background material on the subject of WBV will be presented.

The exposure of workers to mechanical vibration in nonmining industries and agriculture is a concern of safety and health specialists throughout the world. The basis of this concern is that mechanical vibration can interfere with comfort and worker efficiency, be a source of accidents, induce fatigue, and perhaps have detrimental health effects. WBV is a form of mechanical vibration that is transmitted to the human body through its supporting surface, be it the feet of a standing person, the buttocks of a seated person, or the supporting area of a reclining person. WBV is an environmental stressor, as is light, heat, cold, or noise. However, these other stressors impinge on a specific body receptor, such as the eye or ear, while WBV is a diffuse stimulus or broad stressor that impinges on many body organs simultaneously. Although physiological effects of WBV on the human body have been measured numerous times, the long-term health effects of WBV have not been established.

In 1979, the Bureau sponsored work to determine the extent of WBV exposure for operators of mobile underground coal mining equipment (*1*).[5] The equipment studied consisted of continuous miners, cutting machines, gathering arm loaders, scoop tractors and load-haul-dumps (LHD's), shuttle cars, coal drills, and personnel carriers. It was found that, overall, 39 pct of the operators of this equipment were exposed to levels exceeding the fatigue-decreased proficiency (FDP) boundary, while 14 pct were exposed to levels exceeding the exposure limit (EL) boundary. The FDP specifies a limit beyond which exposure to WBV can be regarded as carrying a significant risk of impaired working efficiency for physical tasks. The EL estimates the maximum safe exposure for WBV in terms of frequency, duration, and direction by doubling the FDP corresponding accelerations. The highest levels of WBV were measured for the haulage vehicles: shuttle cars, scoop tractors, and LHD's. For these vehicles, the FDP was exceeded for 55 pct of the operators and the EL for 22 pct. The FDP was exceeded by 28 pct of the continuous miner operators, but the EL value was exceeded by only 2 pct. For personnel carriers, the FDP was exceeded in 16 pct of the cases studied, and the EL in 6 pct. For the other equipment, the data obtained did not permit rigid conclusions to be made. These boundaries were established by the ISO for the evaluation of WBV exposure. The FDP boundary specifies a limit beyond which exposure to vibration can be regarded as carrying a significant risk of impaired working efficiency in many kinds of tasks, particularly those in which time-dependent effects (fatigue) are known to worsen performances, such as in vehicle driving. The EL boundary is set at approximately half the acceleration estimated to be the normal threshold of pain for healthy human subjects seated on a vibrating seat. These same boundaries have been adopted by the American National Standards Institute (ANSI).

What these data indicate is that a significant number of mobile equipment operators in U.S. underground coal mines are exposed to WBV levels that exceed those adopted by ANSI to preserve operator proficiency and/or health and safety. An additional concern is the jarring effects to operators of the impacts or shocks (not WBV) experienced while traveling at relatively high speeds on rough underground haulage roads. Primarily because of environmental conditions, seating designs for underground equipment are still rather primitive, with some of the latest machine models continuing to utilize bent steel plates bolted directly to the vehicle frame as the only means of operator support. This results in an inevitably rough ride, particularly for vehicles operating in thinner seams, where height restrictions further limit seating options. Also, both active and passive restraints are still practically nonexistent for underground equipment.

From an engineering point of view, the design of seating for underground mobile equipment is a formidable task. The seat must be able to handle the high-energy impacts caused by the rough haulage road with little or no clearance for dissipating the energy. It must also withstand a wet, dirty environment and rough handling, which can render a nylon-covered seat cushion useless in a matter of weeks. Also, there is no information for the engineer to refer to that would assist in positioning the equipment operator to minimize the effects of the WBV and the impact energy that are transmitted through the vehicle frame. It is little wonder that past attempts at improving seating by equipment manufacturers have met with little success.

[5] Italic numbers in parentheses refer to items in the list of references at the end of this report.

With this relatively brief background, it is now possible to present the goals of the Bureau's current research into WBV and seating design for underground mobile equipment: (1) To gather additional information on the WBV exposure of underground equipment operators; (2) To determine, through a series of laboratory experiments, the effects that exposure to WBV and impacts have on proficiency and comfort of underground equipment operators; (3) To determine, through additional laboratory experiments, those seating postures, suspension systems, and restraint devices that would minimize the effects of WBV and impacts on underground equipment operators; and (4) To ultimately provide a source document for engineers to assist them in designing equipment so as to minimize WBV exposure to its operators.

After presenting the highlights from an extensive literature survey on WBV, shock, and seating, this report describes the methodology being used to meet these goals. The techniques for gathering and analyzing vibration data taken from the field are also described, as well as the methods used in the laboratory experiments performed to date. The first preliminary results of the work are presented, along with a discussion of the future direction of this project and its possible impact on mining safety.

This work was done in support of the Bureau's goal to enhance the health and safety of the Nation's miners.

SUMMARY OF LITERATURE REVIEW

Although this project deals with mobile underground mining equipment, the preponderance of the literature on WBV and seating has to do with laboratory experiments that were performed in connection with machinery used on the surface. This machinery includes automobiles, trucks, buses, trains, snowmobiles, farm tractors, and other off-road equipment. More than 200 publications having to do with WBV, shock, and/or seating were reviewed. Unfortunately, there have been very few studies done concerning vibration and/or shock and underground mobile mining equipment and even fewer having to do with seats for this equipment.

The following summarizes the most relevant highlights of the literature review. These are grouped by topic into sections for ease of understanding.

INTERNATIONAL STANDARDS ORGANIZATION DOCUMENT 2631

The present ISO standard for human response to WBV (ISO 2631) has been in effect since 1974, with revisions in 1978 and two addenda in 1982 (*2*). It is used to assess the effect of environmental vibration on human health, efficiency, and comfort for vibrations transmitted to the human body in the frequency range from 1 to 80 Hz. The second addendum includes graphs of severe discomfort boundaries and reduced comfort boundaries (RCB) for z-axis (vertical) vibration in the 0.1- to 1.0-Hz range. Above 80 Hz, those who established the standard believe that any effects on the body due to vibration are dependent on so many variables that no generally valid recommendations can be made. ISO 2631 shows how to evaluate the WBV spectrum for discrete (single) frequencies, discrete (multiple) frequencies, narrow-band "random" vibration concentrated in a one-third octave band or less, and broadband vibration. Root mean square (RMS) values of acceleration play a prominent role in the suggested analyses. The direction, frequency, intensity, and duration of WBV are all considered.

Exposure to WBV is defined in terms of its effects in three situations: (1) working efficiency, as shown by the fatigue-decreased proficiency boundary or FDP, (2) health and safety, as given by the exposure limit or EL, and (3) comfort, as shown by the reduced comfort boundary or RCB (fig. 1).

There have been criticisms leveled at ISO 2631. For example, Oborne (*3*) claimed that time of exposure had not been proven to be associated with performance or comfort and that the frequency weightings apply solely to simple sinusoidal vibrations. Corbridge and Griffin (*4*) pointed out that a single frequency weighting is defined for the vertical axis and a second weighting is used for the two horizontal axes. Hansson and Wikstrom (*5*) criticized the standard on the grounds that it is based primarily on laboratory studies in which young people, mostly males, were exposed to sinusoidal vibration along the vertical axis. Griffin (*6*) expressed doubts about the shape of the frequency weightings and the method of assessing complex motions. Fox and Matthews (*7*) claimed that the standard is based on the results of studies of the acute (short-term)

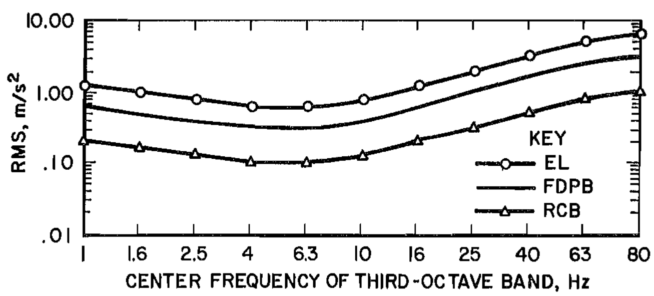

Figure 1.—International Standards Organization acceleration limits (8-h limits). EL, exposure limit; FDPB, fatigue-decreased proficiency boundary; RCB, reduced comfort boundary; RMS, root mean square.

effects of WBV, which are assumed to be related to chronic (long-term) health effects, but this contention has not been proven. Seidel and Heide (*8*) commented that the EL advocated by the standard is not completely safe.

HEALTH AND PHYSIOLOGICAL EFFECTS OF WHOLE-BODY VIBRATION

The National Institute of Occupational Safety and Health (NIOSH) performed studies on the relationship between WBV and the health of heavy equipment operators (*9*), interstate truck drivers (*10*), and motor coach operators (*11*). These studies suggested that low-frequency vibrations are associated with an increased incidence of lower back pain, disk and vertebra degeneration of the spine, gastrointestinal disorders, respiratory problems, ischemic heart disease, and hemorrhoids. However, the increased incidence of these ailments among various operators could not be attributed to WBV alone. Other contributory factors could have been keeping a fixed-seat posture, irregular or poor eating habits, and/or intermittent physical lifting. The fact that some of these workers left their jobs for various reasons also makes interpretations of the data overly subjective.

Spear, Keller, and Milby (*12*) compared the morbidity of machine operators in the construction industry who were exposed to WBV with that of a control group not subject to WBV but working at similar sites. Out of 30 disease categories checked, only three (diseases of other endocrine glands, diseases of the male genital organs, and fracture of a limb) were significantly higher for the operators than for control group workers. The authors stated that even the higher incidence of these three diseases might be due to a selection factor among those who leave and those who stay on at certain jobs.

A literature review by Seidel and Heide (*8*) on the long-term health effects of WBV mentions more than 40 publications that deal entirely or in part with the spine and WBV. Conclusions given were as follows: (1) Workers who are exposed to WBV in their primary job and sometimes are required to do additional heavy physical work are more susceptible to back injury; (2) Long-term exposures to WBV near to or in excess of the ISO 2631 EL seem to carry health risks; and (3) There is no way at present to determine pathological changes in the human body due to WBV for frequencies below 20 Hz.

Helcamp, Talbott, and Marsh (*13*) reviewed the literature on the health effects of WBV and found that workers who spend half or more of their time on the job driving a motor vehicle are three times more likely to develop an acute herniated lumbar disk than persons who do not hold such jobs. Reasons given for this are as follows: lack of proper seat support, continual vibration and mechanical stress from stopping and starting, and prolonged sitting.

On the other hand, there does not appear to be any conclusive evidence that workers who are exposed to WBV suffer from any more frequent or severe ailments than workers who are not so exposed (*13-16*). In other words, detrimental health effects from prolonged work exposures to WBV have not been clearly established. However, the authors of these studies did state that the well-known fact of the presence of discernible physiological effects due to WBV necessitates sober consideration of the possibility of detrimental health effects and of the existence of safe limits for exposures.

The physiological effects of WBV have been studied in terms of heart rate; blood pressure; oxygen uptake (energy consumption); electrocardiogram changes; frequency of breathing; regulation of ventilation; volume of ventilation; gastric functions; and flow of afferent nerve pulses from the sense organs of the joints, muscles, skin, tendons, etc. (*17*). Overall, experiments have shown a raised level of circulatory and respiratory activity at the beginning of exposure to WBV followed by a regression toward resting values or else a constant level close to or slightly above the resting level. Physiological changes in the human body due to WBV are well established but their long-term health effects are not known, although Carlsoo (*14*) thought that medical problems were sure to ensue in time.

COMFORT, PERFORMANCE, AND FATIGUE

There have been a multitude of studies on the effects of WBV on comfort both in the laboratory and in the field. A review of the work done over a 40-year period on the relationship between WBV and comfort showed that the vibration of subjects in one, two, and three dimensions and in roll, pitch, and yaw has been studied in the laboratory and in the field, but in almost all cases the laboratory experiments were restricted to sinusoidal inputs using short testing times and seldom in more than one dimension (*18*). Experiments involving small seat backpan angles (subjects seated nearly upright) were associated with stomach, abdomen, and head discomfort, while large angles were associated with upper back, neck, and sacral discomfort (*19*).

According to Kjellberg and Wikstrom (*17*), the four basic methods used to determine the comfort (or discomfort) of subjects exposed to WBV are as follows: (1) Predictive ratings—Subjects are exposed for a limited time to different levels of a vibration and are told to estimate how long a duration they would be prepared to accept; (2) Semantic scales—Category scales with verbally defined scale steps are used, and subjects are asked to rate their experienced discomfort following exposure to different vibration intensities, frequencies, and durations; (3) Magnitude estimations—This method uses psychophysical scaling, which gives an equidistant scale and hence considers the effect of exposure time. Subjects rate discomfort in the same manner as for semantic scales; and (4) Matching methods—Subjects are exposed to vibrations of different durations, and after a pause, each of these vibrations is followed by a vibration of constant duration, which subjects are asked to adjust to a level that produces the same level of discomfort as the preceding one.

Oborne (*18*), based on the results of his extensive review, concluded that there is a lack of acceptable experimental reports concerning the relationship between WBV and comfort.

The primary performance effects of WBV on operators of mobile underground mining equipment are on visual and manual tasks with decrements in visual acuity occurring most prominently in the 10- to 30-Hz frequency range (*20*). On the whole, Kjellberg and Wikstrom (*17*) found from their literature review that there is no empirical support for the idea that either visual acuity and tracking (eye-hand) or central nervous system reaction time and problem solving task performance deteriorates over time as an effect of vibration. Desrosiers (*21*) found a significant difference in visual acuity and in manual dexterity scores before and after shifts among LHD operators in underground mines, underground workers exposed to poor lighting but not exposed to whole-body or hand-arm vibration, and aboveground workers in good lighting and not exposed to vibration. Hasan (*22*) in a literature review noted that WBV affects body equilibrium and equilibrium control and elicits muscle pain, cramps, and reduced muscular strength, all of which can affect performance.

There have been thousands of studies on the effects of fatigue, especially in manufacturing and athletics and with respect to driving. Fatigue affects human performance (errors made, productivity) and is associated with an increased number of accidents. However, there has been very little research done to determine the direct effects of WBV on fatigue, much less any synergistic effects it might have when combined with the tasks being performed. Equipment design may create two different types of fatigue: physiological fatigue, in which the operator's muscles are overstressed, and psychological or mental fatigue, which may be caused by such design-induced stress as complexity, high accuracy demands, or environmental factors like noise (*23*). Boredom can cause a person to become fatigued just as much as overwork does, but boredom is extremely subjective. Energy expenditure requirements for performing various jobs have received attention, and formulas are available for calculating the length and frequency of rest periods needed for jobs requiring various amounts of energy. This information is available for underground mining (*20, 24-25*).

SHOCK

Shock can be defined as a disturbance or excitation pulse of displacement, velocity, acceleration, or force that is of short duration compared with the characteristic period (time for the vibration to repeat its normal motion) of the system (*26*). Injuries to operators of mobile underground mining equipment due to shock have occurred when the operator hits his or her head on the top of the canopy or on the control levers, or from having his or her elbows, shoulders, or arms strike the machine frame (*27*). ISO 2631 states that its criteria can be applied provisionally to shock-type excitation insofar as the energy is contained within the 1- to 80-Hz band.

The five most common types of shock motions are impulse, step, half-sine, decaying sinusoid, and complex (*28*). If the shock excitation is brief, the system quickly reverts to free vibration at its own natural frequency. Allen did work on the use of a spinal analogue to compare human tolerance of repeated shocks with tolerance of vibration (*29*) and on biodynamic modeling in relation to specification for human tolerance of vibration and shock (*30*). In the first paper, he compared theoretically the compatibility between tolerance of vibration as defined in ISO 2631 and tolerance of repeated shocks as defined by him. He found that the ISO 2631 EL for vertical vibration and the limit for the severe discomfort boundary for tolerance of repeated shocks were compatible for crest factors (peak value divided by RMS) up to 3. He calculated that crest factors up to 4 would be acceptable but that a proposed crest factor of 6 would be too great with respect to present repeated shock criteria. In the second paper, Allen briefly reviewed previous work on dynamic modeling as related to its application to standards for human tolerance of vibration and shock. He then presented a single system whole-body analogue (one mass, one spring, one damper) and a double system head and body analogue (two masses, two springs, two dampers). Equations were derived for these systems and used to obtain input acceleration versus frequency curves.

Mertens and Vogt (*31*) developed a computer model of the human body for estimating the response of seated humans to different types of shocks. The model was tested using different input pulse shapes (rectangular, trapezoidal, half-sine, ejection) and by calculating the resulting forces and mass displacements. The model was able to predict the forces in the vertebral column for the arbitrary input pulse shapes. Other facts of interest are as follows: Motions of the same frequency and same RMS value cause greater discomfort as the peak values increase (*32*), the higher the shock level the fewer the number of shocks the body can tolerate during a particular workday (*33*), and how often a crest factor occurs is more important than the value of the crest factor (*34*). A research study found that 41.5 to 58.0 pct of the crest factors for underground LHD's exceeded 6 (strong shock) under normal operating conditions, but 92 pct of the crest factors exceeded 6 when the seat suspension was released (*21*).

The Air Standardization Coordinating Committee has developed a Dynamic Response Index (DRI) that it is believed quantifies the dynamic compression peak loads in the spinal column that cause injury or discomfort because of shock. The committee (*33*) contends that the body can withstand a certain maximum number of shocks on any one day (the higher the shock level, the fewer the number of shocks), recovery from shocks takes place, and a similar dose can be taken the next day. It is admitted that in the case of very violent shocks injury may occur, and longer than 24 h is needed for recovery (*33*).

SEATS AND SEAT MATERIALS

Agricultural, construction, earthmoving, surface mining, and materials-handling equipment generally have a comfortable seat, a suspension system, an adjustable backrest, a fore-and-aft track adjustment, and sometimes an armrest and a lumbar support. Mobile underground mining equipment generally has a foam pad or cushion on the floor, or simply a steel seat that lacks backrest or backrest track adjustment, suspension system, armrest, or lumbar support.

Seat pan shape, upholstery, slope, height, and width; backrest shape, height, width, curvature, and angle, and the space between the seat pan and the backrest; armrest height, width, length, and separation; and footrest shape, height, surface area, curvature, angle, and adjustability are factors that should be considered when designing an equipment seat, backrest, armrest, and footrest for mobile equipment. The Society of Automotive Engineers (SAE) has published recommendations on seat dimensions for the operator of construction and industrial equipment. Values are given for seat cushion height, length, width, and angle; seat back height, width, and angle; and horizontal and vertical adjustment (*35*).

Carlson and Hoffman (*36*) claimed that seats should be adjustable in the horizontal plane with seat travel of at least 5 in, preferably 6 in. Vertical seat adjustment is desirable to afford good visibility to operators of different heights. The seat angle should be adjustable to at least three positions and ideally infinitely variable through the adjusting range. Armrests should tilt up out of the way when not in use and be adjustable both in height and angle.

Grandjean (*37*) gave recommended guidelines for the ergonomic design of seats as follows:

1. A comfortable body posture requires angles of 90° to 110° for the feet, 110° to 130° for the knees, 20° to 40° arms versus vertical line, 100° to 120° for the hips, and 20° to 25° axis head-neck to axis of the trunk;
2. A movable seat in the backward-forward direction with a minimum range of 6 in and an adjustable backrest angle between 90° and 120° is an absolute necessity;
3. The seat depth should not be shorter than 17.5 in and not exceed 22.0 in;
4. The seat angle should not be smaller than 10° and should not exceed 22°;
5. The backrest should have a lumbar support 4 to 5.5 in above the depressed seat surface and should be slightly concave in the thoracic region with an appropriate height of 20 in above the depressed seat surface; and
6. In order to improve the position of the hips and the trunk, side supports should be used for the seat surface as well as for the backrest.

A study of mobile underground coal mining equipment (*27*) found that none of the seat designs being used provide any insulation of the operator from WBV nor do they provide a means of absorbing the shocks transmitted to the vehicles as they traverse the irregular mine floor. There has not been any systematic and serious attempt to design and develop a seat for mobile underground mining equipment that will significantly reduce WBV and shock, improve comfort and performance, and lessen fatigue. The present seating arrangements and seats for mobile underground mining equipment with the highest vibration levels are inadequate for reducing WBV to ISO 2631 acceptable levels and for attenuating shock. The seats and seating arrangements have virtually ignored comfort, and they affect performance and fatigue in a negative way.

In general, laboratory studies of WBV have had subjects sit on a seat made of wood, aluminum, or wood attached to an aluminum plate and seldom used a backrest or footrest. Occasionally, an automobile or an airplane seat was used but not with the intention of studying seat design as it affects the transmission of vibration.

There are driver seats available on the market that use a variety of seat materials and that can be fitted to agricultural tractors, construction machinery, off-road vehicles, surface mining machinery, forklift trucks, commercial vehicles, and passenger vehicles. A number of companies sell seat cover materials, seat cushion materials, and/or vibration-damping materials. A variety of seat upholstery materials are available that are durable; resistant to tears, stain, abrasion, water, most oils and chemicals, grease, rot, and mildew; and flame retardant. The use of polyurethane foams, which can dampen vibration, on seats or as seat cushions for underground mining equipment must be approved by the Mine Safety and Health Administration, since these substances can emit toxic fumes when subjected to fire.

In summary, there is much that is known about seat design for mobile machinery, and there are many types of seats and materials available to use on these seats to absorb vibration and/or shock to the operators, but little of this knowledge or available seats and seat materials have been applied to underground mining.

SUSPENSION SYSTEMS

Vibration and shock that may affect a vehicle operator's comfort, operating efficiency, safety, and health can often be reduced through the use of proper suspension systems that can be applied to the chassis of a vehicle, the operator's cab or compartment, or the operator's seat. A significant amount of effort has been expended by various manufacturers to develop suspension systems, particularly for seats, to minimize low-frequency, terrain-induced vibrations on off-road vehicles such as scrapers (*38*) and other mobile construction or earthmoving equipment (*39-40*). Computer simulation of off-road vehicle ride dynamics has involved the use and gradual sophistication of mathematical models (*41*), including several for agricultural tractors (*42-45*).

Typically, operators of mobile underground mining equipment and off-road vehicles are subjected to two types of vibration: (1) the relatively low-frequency vibration induced by the tires and the terrain or underground mine floor, and (2) high-frequency vibration originating in the various machine components, such as the engine or geartrain (*46*). Shock can come about through hitting an object or a pothole. Low-frequency vibration is a major source of vibration on these machines and is difficult to attenuate with passive elements that are consistent with other vehicle requirements (*47*). Consequently, ride improvements through using passive seat suspensions are considered limited because of an extremely low natural frequency requirement, particularly in the roll and lateral modes, where an effective seat suspension system must have its natural frequency around 0.25 Hz (*45*).

Mobile underground mining equipment historically has not been equipped with any type of suspension system for the following reasons: the generally harsh environment of underground mines; the extra maintenance required if suspension systems are installed; seam height restrictions; additional costs for these systems; and the lack of any emphasis given to suspension systems or seat designs for this equipment by manufacturers, coal mine operators, or government regulatory agencies.

Conventional seat suspensions for off-road vehicles have been based on a passive isolation method that uses a spring and a damping element. Typically, passive isolation systems amplify vibration occurring at lower frequencies and isolate vibration occurring at frequencies twice the natural (resonant) frequency of their suspensions. In order for passive seat suspensions to isolate low-frequency vibrations (which are common for both aboveground and underground mobile machines as they move over the ground) to a satisfactory extent, they must themselves have a low natural frequency.

Active suspensions that simultaneously sense and compensate for vibration input displacements can be very effective because of their low natural frequency, but the cost and lessened reliability of active suspensions limit their adaptability to ride improvement (*45, 47*).

The isolation of a seat from vibration can be improved by reducing the seat transmissibility resonance frequency to well below the frequencies of dominant energy in the vehicle (down to 1 to 2 Hz) through the use of a low-stiffness suspension mechanism that incorporates, for example, an air or steel spring and a damper. The stiffness of a foam and spring seat cannot be greatly reduced, thus limiting its usefulness, and a seat cushion does not greatly affect the transmission of x-axis vibration to the person but can cause problems if its natural frequency is such that resonance occurs (*41*).

Designing the seat and seat suspension without taking into account the combined effect of the vehicle and the operator does not allow the suspension system to isolate the human body parts from the vibrations to which the vehicle is subjected (*48*).

As was mentioned previously, the worst vehicles with respect to WBV in underground mining are shuttle cars and, to a lesser extent, scoop trams. There were approximately 9,800 of these vehicles in use in underground coal mines in 1982. About 48 pct of the coal mined underground in 1984 came from seams more than 60 in thick, and about 75.1 pct came from seams more than 48 in thick. From these values, it can be estimated that around 4,800 shuttle cars and scoop trams were used in coal mines with seams of more than 60 in, and around 7,350 were used in coal mines with seams of more than 48 in. If suspension systems could be used with very many of these vehicles, then WBV and shock of the operators could be diminished significantly in underground coal mining.

GUIDELINE FORMATS

A survey of reports on guidelines done by the Bureau or under its sponsorship showed that there are *no* standard formats for such reports and that most of these guideline reports devote the majority of their effort to presenting background material and describing the research and development done. In some cases, it was acceptable to give preliminary guidelines and then to discuss what research is needed to strengthen and expand these tentative guidelines. Also, apparently there has not even been a definition of what a guideline is. Seating guidelines have been developed by non-Bureau establishments, but these have no applicability to the Bureau's WBV and seating project.

VIBRATION DATA COLLECTION AND ANALYSIS

Random vibrations, such as those produced by the movement of an underground haulage vehicle over the mine roadway, may be categorized as vibratory processes in which the vibrating object undergoes irregular motion that is unpredictable, that is, its magnitude cannot be specified for any given instant of time. To obtain a complete description of the vibrations, an infinitely long time series record of the signal is theoretically necessary. Of course, this is an impossible requirement, and random vibration signals of much shorter duration are being used in this research study. Statistical techniques utilizing a fast Fourier transform procedure extract the necessary information from the limited data.

Both simple and complex mechanical shocks are like random vibrations in that they are commonly encountered during the operation of underground haulage equipment. A simple mechanical shock may be described as a transmission of kinetic energy to a system that takes place over a relatively short period of time in relation to the normally irregular period of oscillation of the system. Complex shocks may last for several periods of vibration of the system.

For this project, data on both the random vibration and the mechanical shocks created by the haulage vehicle traveling over the roadway were collected. Thus far, only the random vibration has been analyzed for its various frequency components. However, the entire vibration signal collected was used to drive the Bureau's motion platform for the laboratory testing.

The remainder of this section describes the methods used to collect and analyze the vibration data obtained thus far from underground haulage vehicles in coal mines in Pennsylvania, Ohio, and Illinois.

DATA COLLECTION PROCEDURES

The data collection procedure followed the SAE Recommended Practice J1013, JAN80—Measurement of Whole Body Vibration of the Seated Operator of Off-Highway Work Machines. A schematic of the collection system is presented in figure 2, and table 1 describes the specifications of the components of the system. Vibration data were collected at underground coal mines in Pennsylvania, Ohio, and Illinois. All the data were collected in fresh air before the last open crosscut in the section, since the equipment is not certified as intrinsically safe for explosive environments. Vibration modes collected included tramming while loaded and unloaded, dumping and loading. Figure 3 is a typical time series plot of the data collected.

Table 1.—Data collection equipment

Component[1]	*Specifications*
Bruel & Kjaer:	
Seat pad accelerometer, type 4322.	Charge sensitivity: 1 pC/m·s^{-2}, ±2 pct; frequency range: 0.1 to 100 Hz (+5 pct).
Charge amplifiers, type 2635.	Amplifier sensitivity: 0.1 to 10 V/pC; frequency range: 0.2 Hz to 100 kHz.
TEAC R61 4-channel FM data recorder.	Input voltage: ±1 to ±20 V; frequency characteristic: DC to 625 Hz; signal-to-noise ratio: 20 dB.

[1]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

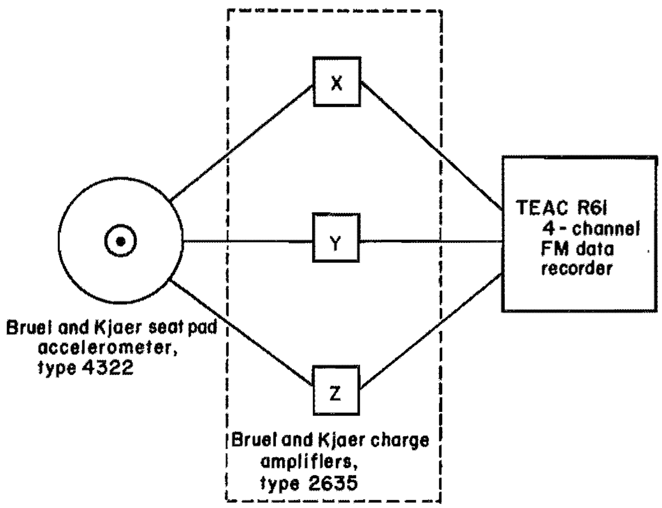

Figure 2.—Field data collection system. Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

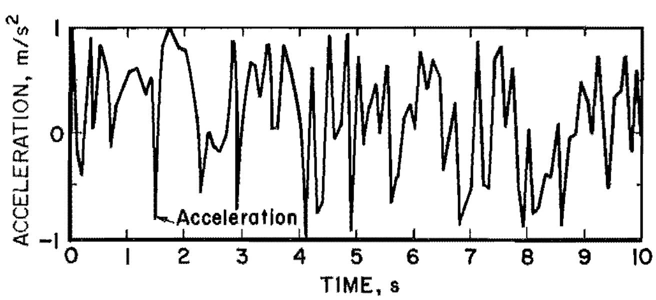

Figure 3.—Time series plot of acceleration.

ANALYSIS OF VIBRATION DATA

The vibration data collected from the underground coal mines were analyzed using two separate procedures. One procedure formatted the data so that they could drive the Bureau's motion platform for laboratory studies of the effects of vibration on seated operators. This is described in greater detail in the section on the laboratory work. The other analysis procedure was used to compare the data with ANSI S3-1979, Guide for the Evaluation of Human Exposure to Whole-Body Vibration. This guide, which is virtually identical to ISO 2631, recommends boundaries for limiting exposure to vibrations transmitted from solid surfaces to the human body in the frequency range from 1 to 80 Hz. See the previous section for more information on the specific applications of this guide.

The steps followed in the analysis of the vibration data were as follows:

1. An analog/digital (A/D) converter and in-house software were used to transfer the data from the tape recorder to a minicomputer. The sampling rate used was 200 points per second (2.5 times the upper limiting frequency of 80 Hz for WBV).
2. Using in-house software, the digitized data were put into a format that could be interpreted by a commercial signal processing software package.
3. Using commercial software, the following analyses were run on the data: time series plots, power spectral density of the time series signal, and RMS value of the time series signal.

The RMS values were then converted into one-third octave component accelerations for the center frequencies specified in table 2. The RMS in each one-third octave band was then graphed for comparison with ANSI's recommended vibration levels.

DISCUSSION OF VIBRATION DATA

The vibration data collected as part of this investigation agree with the results cited in the introduction. Exposures for the rail-mounted mantrip were acceptable during the ride to the face. However, once at the face the operators are frequently exposed at levels higher than the ISO recommendations. This is true in particular for shuttle cars. Scoop operators were found to be exposed to levels in excess of the FDP boundary. This tended to be less of a problem since the scoop operator tends to spend much of his or her time outside of the operator compartment and away from the exposure.

The area of the frequency spectrum at which ISO 2631 recommendations were exceeded tended to be in the natural or resonant frequency ranges of the vertebrae of the neck and lumbar region (2.5 to 5 Hz); trunk, shoulder, and neck (4 to 6 Hz); and head and shoulders (20 to 30 Hz). At this point in the spectrum the recommendations for allowable power are at their minimum. Overall, the amount of energy across the spectrum was fairly constant, perhaps because a shock tends to excite across the entire spectrum and because shocks occurred as the vehicles were driven along the mine floor. This further illustrates the importance of considering shock in designing seating suspensions and padding. Continued data collection will further clarify the degree and time of exposure of miners to WBV and shock and will allow the Bureau to give mine equipment design engineers guidelines on what frequency spectrum to consider in suspension design.

Table 2.—Center frequencies for analysis

Center frequency, Hz	FDPB, m/s^2	EL, m/s^2	RCB, m/s^2
1	0.63	1.26	0.2
1.6	.5	1	.159
2.5	.4	.8	.127
4.0	.315	.63	.1
6.3	.315	.63	.1
10	.4	.8	.127
16	.63	1.26	.2
25	1	2	.317
40	1.6	3.2	.508
63	2.5	5.0	.794
80	3.15	6.3	1

EL Exposure limit.
FDPB Fatigue-decreased proficiency boundary.
RCB Reduced comfort boundary.

LABORATORY STUDIES

In view of the limited amount of data available on the effects of random vibration and shock on mobile equipment operators, a series of experiments were designed to meet the specific needs of this research program. The following sections describe the structure of the initial pilot studies and present the results of an analysis of the data.

EXPERIMENTAL DESIGN

The independent variables in this initial investigation were (1) presence or absence of random, broadband vibration, (2) seat back angle of 90° or 130°, and (3) presence or absence of foam padding material on the seat pan and back. Dependent variables were heart rate (HR); systolic, diastolic, and mean blood pressures (BP); and subjective discomfort.

The subjects were tested on two separate days—one vibrating and the other nonvibrating. During each test day, the subjects were exposed to four different seat configurations (seat back angle of 90° or 130° and padded or steel seat) for a 30-min period (length of a typical duty cycle as determined by discussions with and observations of shuttle car operators) in each configuration. During a subject's two test days, the order of testing the four configurations was the same. However, the order of evaluating the configurations for different subjects was statistically randomized and counterbalanced to control for bias due to the order of testing.

SUBJECTS

Eight healthy men (35.5 years of age ± 6.5 SD) volunteered to participate in a pilot study that examined the effects of vibration, seat back angle, and the presence or absence of foam padding on the various physiological measures mentioned above and on subjective discomfort. The subjects were all employees of the Bureau's Pittsburgh Research Center and were minimally familiar with the test protocol. Potential subjects were advised of the nature of the investigation and signed an informed consent form before undergoing the screening medical exams. They received a thorough physical examination and graded exercise tolerance test prior to participation (*49*).

APPARATUS

Figure 4 presents a schematic of the equipment used in this experiment. Subjects sat in a test seat, which was equipped with an adjustable backrest, to which padding could be easily bolted. One of the configurations tested

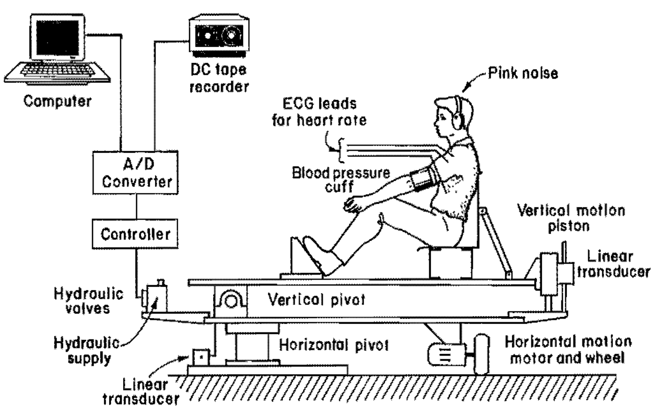

Figure 4.—Schematic of equipment used in experiments. ECG, electrocardiogram.

(90° seat back, no padding) was a duplicate of a typical operator's seat. The adjustable seat was mounted on an electrohydraulically powered, computer-controlled shake table. HR was obtained using a recorder, and BP's were obtained with a noninvasive BP monitor. While the subjects were seated in the various experimental conditions, they wore stereo headphones through which "pink noise" was played to mask extraneous auditory signals. Commercially available foam material was used.

Motion Platform

In order to perform the work described in the previous paragraph, a mechanism was needed to transmit vibrations to human subjects that approximated the exposure received while operating a haulage vehicle in an underground mine. This was done using a hydraulically powered motion platform controlled by a microcomputer and an A/D converter. The following sections describe the structure and capabilities of the Bureau's motion platform.

Motion Platform Framework

The majority of the framework of the motion platform was salvaged from a previously completed Bureau project in which a hydraulically powered shuttle car simulator was constructed for training purposes. The frame is composed of three sections: the anchor plate, the primary frame, and the carrier frame. The anchor plate is bolted to the floor and supports the horizontal pivot, while keeping the motion platform stationary during operation. The primary frame supports the bearings for the vertical pivot and the horizontal pivot assembly. It also provides the mounting for the hydraulic equipment that drives the platform. The carrier frame supports the test equipment, seating fixtures, and human subjects. Both frames are constructed of welded tubular steel. The carrier frame has a 1-in steel plate welded to its upper surface to help damp higher frequency vibrations in the system.

Hydraulic System

A relatively simple hydraulic system is used to drive the motion platform. Hydraulic power is provided by a pump coupled with a 10 hp dc motor. The pump and motor are mounted on a hydraulic reservoir. A water bath oil cooler is installed in the system.

Oil flows from the pump in parallel with two pilot-operated control valves: one for the vertical motion, one for the horizontal motion. The direction of oil flow within these valves is determined by the computer control system. The vertical control valve is connected to a double-acting cylinder mounted at the rear of the motion platform on the platform to move 3 in above or below its neutral position. The horizontal control valve is connected to a hydraulic motor and wheel assembly mounted on the primary frame. The activation of this wheel allows the motion platform to move around the horizontal pivot. Since the horizontal motion capabilities of the platform are not currently being utilized for this project, an additional flow control valve was installed in the hydraulic motor's inlet line. This valve greatly reduces the speed of the platform in the event of an accidental diversion of hydraulic oil to the motor-wheel unit. Another valve between the hydraulic power unit and the control valves monitors oil pressure to the system.

An emergency stop switch is provided on a tether cord and is usually mounted on the carrier frame. This switch cuts off all power to the hydraulic unit and immediately shuts down the motion platform in the event of an emergency.

Control System

The motion platform is controlled with an AT-compatible microcomputer coupled with an A/D converter, two servocontroller boards, and two linear displacement transducers. The procedure for controlling the position of the platform so that it approximates the motion of a piece of mobile equipment is outlined below.

1. A tape recording of acceleration data taken from the frame under the seat of a piece of mobile underground equipment is digitized using the A/D converter. The data are digitized at a rate of 200 samples per second and are stored in a file on the microcomputer's hard disk drive.
2. The movement of the motion platform is dependent on position-related information. For instance, the platform reacts to commands telling it where to go, and not to information telling it how fast to move. For this reason, the acceleration data are converted to data on the vertical distance traveled using the equation

$$\text{current position} = {}^{1}/_{2}at^{2} + v_{o}t + d_{o},$$

where a = initial acceleration as measured on the vehicle frame,

v_o = initial velocity of the test vehicle in the direction of the acceleration measurements,

d_o = current displacement of the test vehicle in the direction of the acceleration measurements,

and t = .002 s, the time between acceleration samples.

Samples were taken 200 times per second. This conversion of acceleration data is accomplished using in-house software, and the data are stored in the random-access memory of the microcomputer.

3. The digital position data are output as an analog voltage using the A/D converter. The signal is received by the servocontroller, which compares the incoming position signal with the current position of the platform as transmitted by the linear displacement transducer. The servocontroller then opens the control valve to permit oil to flow in the proper direction to allow the platform to move into a position to match the input signal.

While this method of controlling the motion platform makes it difficult to exactly match the vibration spectrum of an underground haulage vehicle, it does produce a realistic "ride" that is a close approximation to the real thing. Several shuttle car operators tested on the platform attested to its similarity to the type of ride they were used to.

EXPERIMENTAL TASK

Figure 5 provides a typical one-third-octave band power spectrum of the vibration generated by the shake table. This spectrum is an average of the four segments of the normal cycle that the coal haulage vehicle (shuttle car) undergoes when moving coal from the mining face to the dumping point for removal to the surface. These segments are (1) loading coal into the stationary haulage vehicle, (2) tramming loaded to the dump point, (3) unloading the coal from the stationary haulage vehicle, and (4) tramming empty back to the mining face.

Data were collected during actual shuttle car operation underground. Vertical vibration signals were collected via a uniaxial accelerometer that was attached to the machine frame directly beneath the operator's seat. These data were processed so the computer-controlled vibration platform could approximate the signals gathered from the shuttle car during operation.

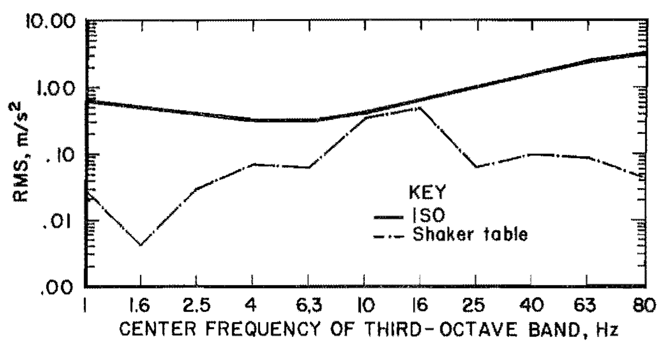

Figure 5.—Comparison of fatigue-decreased proficiency boundary for shaker table with International Standards Organization acceleration limits.

Figure 5 indicates that the composite vibration spectrum to which the subjects were exposed was broadband and very low intensity. The acceleration levels of the spectrum were greater than 0.03 m/s^2 (approximately 0.003 g) from 3.15 to 80 Hz. The maximum acceleration of the vibration peaked at 10 Hz at approximately 0.3 m/s^2 (approximately 0.03 g) and at 12.5 Hz at slightly less than 0.4 m/s^2 (approximately 0.04 g).

Prior to testing, the subject was instructed as to the experimental protocol and how to fill out the discomfort form on which the subject rated the level of discomfort from 1 (very comfortable) to 10 (very uncomfortable). The subject was then positioned in the seat. Before beginning the 30-min test period, each subject was instructed to sit quietly so resting HR and BP levels could be obtained.

During testing, HR was collected during the last 10 s of every minute. The final 25 HR values were averaged and taken as the mean value for that test configuration. BP's were collected every 5 min during programmed pauses (shaker table motionless) in the vibration cycle. Systolic, diastolic, and mean values were averaged at the end of the test. Every 10 min (at minute 9, 19, and 29) the subjective discomfort form was also completed. After the test period, a 30-min break was provided for the subject to attend to personal needs and to recover by relaxing in a reclined posture before beginning the next experiment.

DATA TREATMENT

The results of data collected for the six dependent measures were analyzed using a 2 × 2 × 2 (vibration or not × seat back angle × seat material or not) analysis of variance with repeated measures (ANOVR) statistical package. Critical alpha levels were considered to be 0.05 in all cases.

PILOT STUDY RESULTS

Physiological Data

HR ($p < 0.01$), systolic BP, and mean BP ($p < 0.05$) were all significantly increased during the vibrating test day. The vibrating condition caused a 9.3-pct increase in the average HR (for all test configurations) over the non-vibrating conditions (69.9 to 76.4 beats per minute; $F_{1,7} = 14.538$, $p = 0.007$, where F stands for the ratio of the variances, and p the probability of this change occurring by chance). Neither the HR nor the BP were significantly affected by the angle of the seat back or the presence or absence of foam material. The systolic BP increased 3.2 pct in the average value for all test conditions from the nonvibrating day (127.1 mm Hg to 131.2 mm Hg; $F_{1,7} = 9.006$, $p = 0.020$). Additionally, the vibrating test condition caused a 4.4-pct increase in the mean BP for all test configurations (96.7 mm Hg to 100.9 mm Hg; $F_{1,7} = 11.052, p = 0.013$).

Subjective Discomfort Data

The lower portion of table 3 presents the subjective discomfort data. The number of times the subjects reported discomfort was significantly affected by whether they were seated in the untreated (steel) seat or in the seat treated with foam padding (an average of 20.7 times for the evaluation of the steel seat versus 16.5 times for the padded seat; $F_{1,7} = 10.920, p = 0.013$) and also whether the subject was vibrating or not (an average of 20.8 times for the vibrating condition versus 16.4 for the nonvibrating condition; $F_{1,7} = 6.927, p = 0.034$). Similarly, the overall rating of discomfort was significantly affected by both the vibrating test condition (an average of 2.27 for the vibrating tests versus 1.76 for the nonvibrating conditions; $F_{1,7} = 11.097$, $p = 0.013$) and whether the subjects were sitting in the steel seat or the padded one (an average of 2.27 for the steel seat versus 1.76 for the padded seat; $F_{1,7} = 26.989$, $p < 0.001$). Neither the number of times the subjects reported discomfort nor the overall discomfort rating was significantly affected by the angle of the seat back.

Table 3.—Summary of effects for all test conditions[1]

Dependent variables	Vibration or no vibration[2]	Steel or foam padded[3]
Heart rate	$F_{1,7} = 14.538$; $p = 0.007$.	NS.
Blood pressure:		
Systolic	$F_{1,7} = 9.006$; $p = 0.020$.	NS.
Diastolic	NS	NS.
Mean	$F_{1,7} = 11.052$; $p = 0.013$.	NS.
Subjective discomfort:		
Number of evaluations	$F_{1,7} = 6.972$; $p = 0.034$.	$F_{1,7} = 10.920$; $p = 0.013$.
Overall ratings	$F_{1,7} = 11.097$; $p = 0.013$.	$F_{1,7} = 26.989$; $p < 0.001$.

F Ratio of variances.
NS Nonsignificant value.
p Probability of results being obtained.
[1]Back angle of 90° or 130° = NS.
[2]Dependent variables increase with vibration.
[3]Dependent variables decreae with padding.

CONCLUSIONS

1. The present standard for human response to WBV (ISO 2631), although criticized in some respects, is nonetheless generally accepted worldwide as the best standard available for the evaluation of working efficiency (fatigue-decreased proficiency boundary), health and safety (exposure limit), and comfort (reduced comfort boundary).

2. WBV has been shown to cause numerous physiological effects in operators of many types of machinery, but it has not been proven that these physiological responses result in any detrimental health effects or any specific disease.

3. Although it is agreed that WBV of sufficient intensity and frequency gives rise to discomfort, there is a lack of acceptable experimental reports concerning the relationship between WBV and comfort, that is, the results obtained by researchers trying to determine the relationship between WBV and comfort are inconsistent.

4. The primary effects of WBV on operators of mobile underground mining equipment are on visual and manual tasks, with a loss of visual acuity occurring most prominently in the 10- to 30-Hz frequency range.

5. There has been very little research done to determine the direct effects of WBV on fatigue (either physical or psychological), much less any synergistic effects it might have when combined with the tasks being performed.

6. Injuries to operators of mobile underground mining equipment due to shock (hitting a pothole, striking an object) have occurred when the operator hits his or her head on top of the canopy or on the control levers, or from having his or her elbows, shoulders, or arms strike the machine frame.

7. The seats and seat materials (if any) often used at present for mobile underground mining equipment can be improved upon in order to attenuate WBV and shock.

8. Seating guidelines have been developed for non-mining vehicles operated on the surface, and these might be applicable with some modifications to mobile underground mining equipment.

9. Suspension systems, used widely for many types of machinery operated on the surface, might be practical for much of underground coal mining where the seam height is sufficiently great.

10. The worst vehicles in underground coal mining with respect to WBV are shuttle cars, scoop tractors and load-haul-dumps, and personnel carriers.

11. Results of experiments performed at the Bureau's vibration laboratory (using a motion platform driven vertically by converted signals obtained from measuring shuttle car vibration in the field) showed that heart rate, systolic blood pressure, mean blood pressure, and discomfort all increased significantly (statistically) when the subjects were vibrated. Neither heart rate nor blood pressure were affected significantly by changes in the seat angle or the presence or absence of foam material on the seat, but discomfort did increase significantly in the absence of foam material.

RECOMMENDATIONS FOR FUTURE WORK

The ultimate goal of this research project is to develop guidelines for the designers of underground mobile equipment operator compartments so that the effects of WBV and shock can be minimized. The results of the present study have raised several points to be considered in future testing:

1. The low-seam underground environment often requires the equipment to be operated while drivers are lying on their backs or sides. While there were no significant effects on any of the dependent measures from the two seat back angles investigated in the present study, future research should investigate more supine postures.

2. The 30-min vibration period was chosen based on estimates of the duty cycle of underground coal haulage equipment. A longer vibration period or shorter rest period may be more appropriate to provide an accurate description of the WBV effects.

3. Back extensor muscle endurance should be measured to determine if WBV will adversely affect this variable.

4. The effects of comfort on performance and fatigue for operators of mobile underground mining equipment should be investigated.

5. Shock should be introduced in laboratory experiments to determine its physiological and performance effects.

6. Suggested seating guidelines for mobile underground mining equipment should be developed.

7. Suspension systems should be investigated for their possible application to underground mines with sufficient seam thickness. This could be done by either modifying a commercially available system or by fabricating a novel type.

8. Seat materials that are commercially available and combinations of these seat materials that would attenuate WBV and shock should be tested.

REFERENCES

1. Remington, P. J., D. A. Andersen, and M. N. Alakel. Assessment of Whole Body Vibration Levels of Coal Miners. Volume II: Whole Body Vibration Exposure of Underground Coal Mining Machine Operators (contract JO308045, Bolt Beranek and Newman Inc.). BuMines OFR 1B-87, Mar. 1984, 114 pp.; NTIS PB 87-144119.

2. International Organization for Standardization (Paris, France). Guide for the Evaluation of Human Exposure to Whole-Body Vibration. ISO 2631, 2d ed., 1978-01-15, 1978, 17 pp.

3. Oborne, D. J. Whole Body Vibration and International Standard ISO 2631: A Critique. Hum. Factors, v. 25, No. 1, 1983, pp. 55-69.

4. Corbridge, C., and M. J. Griffin. Vibration and Comfort: Vertical and Lateral Motion in the Range 0.5 to 5.0 Hz. Ergonomics, v. 29, No. 2, 1986, pp. 249-262.

5. Hansson, J. E., and B. O. Wikstrom. Comparisons of Some Technical Methods for the Evaluation of Whole-Body Vibration. Ergonomics, v. 24, No. 12, 1981, pp. 953-963.

6. Griffin, M. J. The Evaluation of Vehicle Vibration and Seats. Appl. Ergon., v. 1, No. 1, 1978, pp. 15-21.

7. Fox, E. L., and D. K. Matthews. Sensory Feedback for Remote Control of a Continuous Miner. U.S. Dep. Energy Rep. DOE/ET/12458—T12, Jan. 1982, 210 pp.

8. Seidel, H., and R. Heide. Long-Term Effects of Whole-Body Vibration: A Critical Survey of the Literature. Int. Arch. Occupat. and Environ. Health, v. 588, 1986, pp. 1-26.

9. Milby, T. H., and R. C. Spear. Relationship Between Whole Body Vibration and Morbidity Patterns Among Heavy Equipment Operators. NIOSH Rep. 74-131, July 1974, 83 pp.

10. Gruber, G. J. Relationship Between Whole Body Vibration and Morbidity Patterns Among Interstate Truck Drivers. NIOSH Rep. 77-167, Nov. 1976, 62 pp.

11. Guber, G. J., and H. J. Ziperman. Relationship Between Whole Body Vibration and Morbidity Patterns Among Motor Coach Operators. NIOSH Rep. 75-105, Sep. 1974, 69 pp.

12. Spear, R. C., R. C. Keller, and T. H. Milby. Morbidity Studies of Workers Exposed to Whole Body Vibration. Arch. Environ. Health, v. 31, No. 3, 1976, pp. 141-145.

13. Helcamp, J. C., E. O. Talbott, and G. M. Marsh. Whole Body Vibration—A Critical Review. Am. Ind. Hyg. Assoc. J., v. 45, No. 3, 1984, pp. 162-167.

14. Carlsoo, S. The Effect of Vibration on the Skeleton, Joints, and Muscles: A Review of the Literature. Appl. Ergon., v. 13, No. 4, 1982, pp. 251-258.

15. National Academy of Sciences—National Research Council. The Effects of Whole-Body Vibration on Health (U.S. Dept. Navy contract N00014-79-C-0060, CHABA Working Group 79). NR Rep. 201-124, 1979, 10 pp.

16. Pepler, R. D., and T. J. Naughton. Relationship Between Truck Ride Quality and Drivers' Health: Methodology Development (U.S. Dept. Transportation contract DOT-HS-9-02312, Dunlap and Assoc.). DOT Rep. HS-805-603, 1980, 73 pp.

17. Kjellberg, A., and B. O. Wikstrom. Whole Body Vibration Exposure Time and Acute Effects—A Review. Ergonomics, v. 28, No. 3, 1985, pp. 535-544.

18. Oborne, D. J. A Critical Assessment of Studies Relating Whole-Body Vibration to Passenger Comfort. Ergonomics, v. 19, No. 6, 1976, pp. 751-774.

19. Harrah, C. B., and R. W. Shoenberger. Effect of Body Supination Angle on Subjective Response to Whole-Body Vibration. Aviat., Space, and Environ. Med., Jan. 1981, pp. 28-32.

20. Sanders, M. S., and J. M. Peay. Human Factors in Mining. BuMines IC 9182, 1988, 153 pp.

21. Desrosiers, J. The Measurement of Whole Body Vibration and Its Effect on Load-Haul-Dump Operators in Underground Mining Environments. Mine Accident Prevention, Assoc., Ontario, Canada, Final Report, June 1987, 158 pp.

22. Hasan, J. Biomedical Aspects of Low-Frequency Vibration. Work, Environ., Health, v. 6, No. 1, 1970, pp. 19-45.

23. Woodson, W. E. (ed.). Human Factors Design Handbook. McGraw-Hill, 1981, 627 pp.

24. Ayoub, M. M., J. L. Selan, C. L. Burford, K. Intaranont, H. P. R. Rao, J. L. Smith, D. K. Caddel, W. M. Bobo, N. J. Bethea, and H. Chang. Biomechanical and Work Physiology Study in Underground Mining Excluding Low Coal (contract JO308058, Texas Tech Univ.). BuMines OFR 90-85, July 1984, 211 pp.; NTIS PB 85-243566.

25. Ayoub, M. M., N. J. Bethea, W. M. Bobo, C. L. Burford, D. K. Caddell, K. Intaranont, S. Morrisey, and J. L. Selan. Mining in Low Coal. Volume I: Biomechanics and Work Physiology (contract HO387022, Texas Tech Univ.). BuMines OFR 162(1)-83, Nov. 1981, 175 pp.; NTIS PB 83-258160.

26. Thomson, W. T. Theory of Vibration With Applications. Prentice-Hall, 2d ed., 1981, 493 pp.

27. Stobbe, T. J., and R. W. Plummer. Human Factors and Mining Machinery. SAE Tech. Ser. Pap. 840040, Dep. Ind. Eng., WV Univ., Morgantown, WV, 1984, 4 pp.

28. Morrow, C. T. Shock and Vibration Engineering. Wiley, v. 1, 1963, 384 pp.

29. Allen, G. Part I: The Use of a Spinal Analogue To Compare Human Tolerance to Repeated Shocks With Tolerance of Vibration. Human Eng. Div., R. Aircr. Establishment, Hampshire, UK, 1978, 4 pp.

30. ___. Part II. A Critical Look at Biodynamical Modeling in Relation to Specifications for Human Tolerance of Vibration and Shock. Human Eng. Div., R. Aircr. Establishment, Hampshire, UK, 1978, 11 pp.

31. Mertens, H., and L. Vogt. The Response of a Realistic Computer Model for Sitting Humans to Different Types of Shocks. Inst. Aviat. Med., Bonn, Federal Republic of Germany, 1972, 17 pp.

32. Griffin, M. J., and E. M. Whitham. Discomfort Produced by Impulsive Whole-Body Vibration. J. Acoust. Soc. Am., Nov. 1980, pp. 1277-1284.

33. Air Standardization Coordinating Committee. Human Tolerance to Repeated Shock. Advisory Pub. 61/25, Aug. 1982, 9 pp.

34. Barton, J. C. Off-Road Machine Operator Vibration Measurement Methods. Paper in Earthmoving Industry Conference (Peoria, IL, April 6-8, 1981). SAE, Warrendale, PA, 1981, 19 pp.

35. Society of Automotive Engineers. Operators' Seat Dimensions: Construction and Industrial Equipment Design. SAE J899, SAE Handbook, 1964, pp. 1669-1670.

36. Carlson, L. E., and A. G. Hoffman. Development of Improved Seatbelt Systems for Surface Mining Equipment (contract HO202005, Mobility System and Equipment Co.). BuMines OFR 28-83, Oct. 1981, 127 pp.; NTIS PB 83-171991.

37. Grandjean, E. Sitting Posture of Car Drivers From the Point of View of Ergonomics. Ch. in Human Factors in Transport Research: User Factors—Comfort, The Environment, and Behavior, ed. by D. J. Oborne and J. A. Lewis. Academic, 1980, pp. 205-213.

38. Cadou, P. B., and F. J. Bowser. The Development of a Scraper Suspension System. SAE Tech. Pap. Ser. 780462, Earthmoving Machinery Conference, Central Illinois Section (Peoria, IL, Apr. 10-12, 1978). 1978, 8 pp.

39. Koutsky, L. J. Development of a Suspension Seat for Earthmoving Vehicles. SAE Tech. Pap. Ser. 780474, Earthmoving Industry Conference, Central Illinois Section (Peoria, IL, Apr. 10-12, 1978). 1978, 11 pp.

40. Zach, D. J. The Development of a Seat Suspension for Mobile Construction Equipment. SAE Tech. Pap. Ser. 720515, Earthmoving Industry Conference, Central Illinois Section (Peoria, IL, Apr. 5-7, 1971). 1971, 10 pp.

41. Fairley, T. E., and M. J. Griffin. Modelling a Seat-Person System in the Vertical and Fore-and-Aft Axes. Inst. Mech. Eng., Pap. C131/84, 1984, pp. 83-89.

42. Kim, H. U., D. L. Hoag, and D. R. Hunt. Ride Simulation of Passive, Active, and Semi-Active Seat Suspensions for Off-Road Vehicles. Am. Soc. Agric. Eng., Trans. ASAE, Pap. 2801, 1985, pp. 55-64.

43. Palanichamy, M. S., M. K. Patil, and D. N. Ghista. Minimization of the Vertical Vibration Sustained by a Tractor Operator. Ann. Biomed. Eng., v. 6, 1978, pp. 138-153.

44. Patil, M. K., M. S. Palanichamy, and D. N. Ghista. Man-Tractor System Dynamics: Towards a Better Suspension System for Human Ride Comfort. J. Biomech., v. 11, 1977, pp. 397-406.

45. Rakheja, S., and S. Sankar. Improved Off-Road Tractor Ride Via Passive Cab and Suspension Systems. J. Vib., Stress, and Reliability Des., Apr. 1984, pp. 305-313.

46. Suggs, S. W., L. F. Stikeleather, and C. F. Abrams, Jr. Field Tests of an Active Seat Suspension for Off-Road Vehicles. Am. Soc. Agric. Eng., Trans. ASAE, Paper No. 69-526, June 1969, pp. 608-611.

47. Stikeleather, L. F., and C. W. Suggs. An Active Seat Suspension for Off-Road Vehicles. Am. Soc. Agric. Eng., Trans. ASAE, Pap. 68-632, Dec. 1968, pp. 99-106.

48. Hall, G. O. Providing Ride Comfort for the Operator of Off-Highway Vehicle. SAE Tech. Pap. Ser. 690567, National Farm, Construction, and Industrial Machinery Meeting (Milwaukee, WI, Sep. 8-11, 1969). 1969, 5 pp.

49. American College of Sports Medicine. Guidelines for Graded Exercise Testing and Exercise Prescription. Lea and Febiger, 1980, 151 pp.

INT.BU.OF MINES,PGH.,PA 29663

*USGPO:1992--709-008/60091